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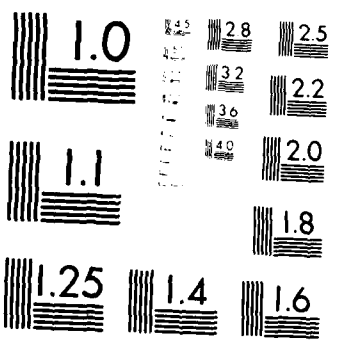

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A laser-amplifying device is described which is based on the simulated decay of excitons in a pure crystal. An estimate is made of the gain of the device. At a typical frequency the gain is found to be appreciably large thus suggesting practical application of the laser amplifier.

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Abstract

A laser-amplifying device is described which is based on the stimulated decay of excitons in a pure crystal. An estimate is made of the gain of the device. At a typical frequency the gain is found to be appreciably large thus suggesting practical application of the laser amplifier.

In a previous article by the authors [1], a lasing mechanism was described based on stimulated decay of excitons. The process depends critically on the non-boson quality of excitons, which in turn may be assured by sufficiently high exciton density. This criterion follows from the fact that the ideal bose commutation relations [2] become increasingly invalid with growth of the number of excited atoms in the crystal.

In the present paper a laser-amplifying device is proposed based on the process described above. Namely, it is proposed that excitons in a pure (insulator or semiconductor) crystal are triggered by incident resonant laser radiation and that excitons are created by an external intermittent radiative source.

Thus, for example [3], exciton decay wavelength in pure ZnS is 3201.71 Å. The crystal could then be used to amplify radiation stemming from a dye laser at the same wavelength. Other characteristic wavelengths appropriate to this device are listed in Table 1.

The device is modeled as follows: Excitons in the pure crystal are created by a flash lamp. The power supply to the lamp has an on-off profile which is π radians out of phase with the pulse frequency of the input laser. The duration between peaks of this profile is of the order of the lifetime of an exciton, $\sim 10^{-6}$ sec.

We assume this modulation has the following effect. Exciton density grows during the 'on' phase of the lamp to a peak value

and then suffers resonant stimulated decay by the input laser radiation during the 'off' phase of the lamp.

During the amplification interval, radiative power flux, $S[W/m^2]$, in the crystal satisfies the equation

$$\frac{dS}{dx} = g\,S \tag{1}$$

where g is the gain,

$$g = \kappa(\rho\sigma_d - \rho_o\sigma_a) \tag{2}$$

In this expression ρ is density of excited atoms, and ρ_o is density of atoms in the general state. It follows that the total density of atoms, ρ_T, is given by

$$\rho_T = \rho + \rho_o$$

The absorption cross section is σ_a and σ_d is the cross section for stimulated decay. Finally κ describes additional loss effects such as, for example, that due to reflection, impurities, miss-match between input and resonant frequencies, etc.

From the principle of microscopic reversibility [4] and assuming non-degeneracy of excited and ground exciton levels, one may set $\sigma_d = \sigma_a$. Furthermore, for σ we may write [5]

$$\sigma(\omega) = \frac{(2\pi)^2 e^2 \omega g_L(\omega) d^2}{3\hbar c} \tag{4}$$

Here $\underset{\sim}{d}$ is the dipole matrix element between Wannier state functions. At the site $\underset{\sim}{\ell}$ it is given by

$$\underset{\sim}{d} = \langle c\underset{\sim}{\ell} \mid \underset{\sim}{r} \mid v\underset{\sim}{\ell} \rangle. \tag{5}$$

Valence and conduction bands are denoted by v and c respectively. This matrix element is relevant to a transition between the ground and excited states of an exciton.

The term g_L in (4) refers to the Lorentzian lineshape factor. On resonance it reduces to [5]

$$g_L = \frac{\tau}{\pi} \tag{6}$$

In this expression τ denotes the decay time of the exciton. As previously noted, $\tau \simeq 10^{-6}$ sec.

A rough estimate of the matrix element (5) may be constructed as follows. We assume that the valence band is comprised of S atomic states and the conduction band is comprised of P atomic states. With

$$\underset{\sim}{s} \equiv \underset{\sim}{r} - \underset{\sim}{\ell},$$

in the coordinate representation, the bra and ket vectors in (5) become, respectively,

$$W_v(\underset{\sim}{s}) = \frac{1}{\sqrt{4\pi}\, a^{3/2}} e^{-s/a}$$

$$W_c(s) = \frac{s\, e^{-s/2a}}{(2a)^{3/2}\, a\sqrt{3}} \sqrt{\frac{3}{4\pi}} \cos\theta \tag{7}$$

where $\cos\theta \equiv \hat{\underset{\sim}{z}} \cdot \underset{\sim}{s}/s$, for an arbitrary z-axis. Furthermore,

$$a = \varepsilon\, a_o^* = \varepsilon\, \hbar^2/m^* e^2$$

where ε is the dielectric constant.

There results

$$d = \left(\frac{2}{3}\right)^6 a \frac{1}{\sqrt{8}} \int_0^\infty ds\, s^4 e^{-3s/2a}$$

$$= \frac{2^8}{\sqrt{2}\ 3^5}\, a \tag{8}$$

with (6) and (8), σ as given by (4) becomes

$$\sigma = 32\pi \left(\frac{2}{3}\right)^8 \alpha\, \omega\, \tau\, a^2 \tag{9}$$

where α is the fine structure constant.

Returning to (2), with (9) we write

$$g = 32\pi \left(\frac{2}{3}\right)^8 \alpha\, \omega\, \tau\, a^2 \kappa\, (\rho - \rho_o) \tag{10}$$

At 55% pumping efficiency, $\rho = 0.55\rho_T$, $\rho_o = 0.45\rho_T$ and (10) reduces to

$$g = 32\pi \left(\frac{2}{3}\right)^8 \alpha\, \omega\, \tau\, a^2\, 0.1\, \kappa\, \rho_T \tag{11}$$

At $\omega \simeq 10^{14}$, $\tau \simeq 10^{-6}$, $a \simeq 0.5$ Å we find

$$g \simeq 7.16 \times 10^{-9}\, \kappa\, \rho_T \tag{12}$$

Thus for $\kappa\, \rho_T > 10^9$, $g > 1$ and the device may be expected to amplify the input laser pulse.

We have described a laser-amplifier device based on stimulated decay of excitons in a pure crystal. An expression for the gain of the device together with a criterion for amplification were obtained. These expressions suggest practical use of the proposed device. The device presumes a non-bose like quality of excitons. This property is satisfied provided a sufficiently large number of atoms are excited, i.e., $\rho \gtrsim \rho_o$.

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[3] D.C. Reynolds and T.C. Collins, "Excitons: Their Properties and Uses", Academic Press, New York, 1981.

[4] R.L. Liboff, "Introductory Quantum Mechanics", Holden Day, Oakland, CA (1980).

[5] R.H. Pantell and H.E. Puthoff, "Fundamentals of Quantum Electronics", John Wiley, New York, 1969.

Table 1

Characteristic Exciton Properties in Selected Crystals [3]

Material	Energy gap E_g (meV)	Binding energy E_b (meV)	Photon energy E_g-E_b (meV)	Wavelength (Å)
Si	1112	14	1098	11290.5 (IR)
Ge	803	3.6	799.4	15507.9 (IR)
ZnO	3436	59	3377	3671.01 (V)
ZnS	3911	39	3872	3201.71 (UV)
ZnSe	2795	281	2514	4931.2 (O)
GaAs	1519	4.2	1514.8	8183.9 (IR)
CdS	2582	28	2554	4853.9 (O)
InSb	235.2	0.4	234.8	52798.1 (IR)

(IR, O, V, UV) ≡ (infrared, optical, violet, ultraviolet)

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